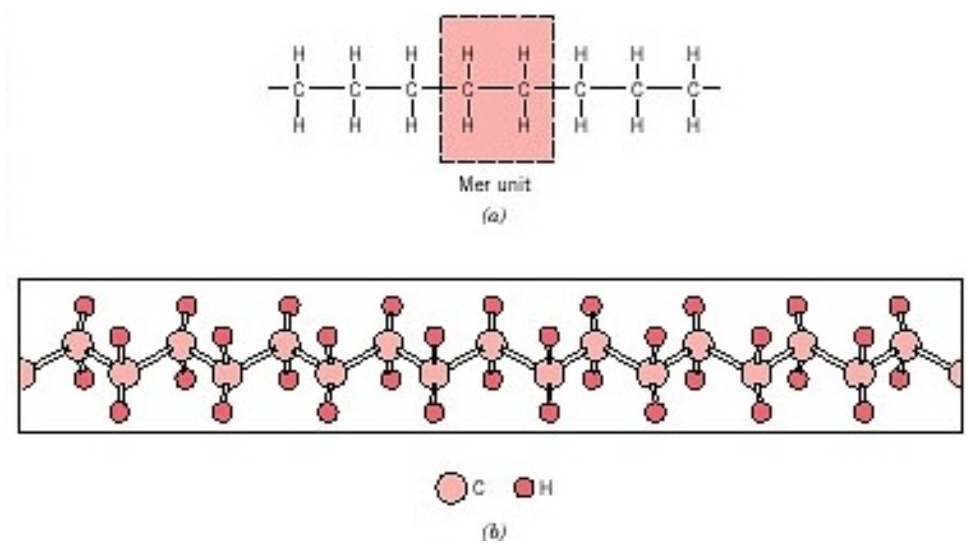
Polymer Processing

Outline

- Polymer Basics
- Injection Molding
  - Process description
  - Analysis
- Compression Molding
- Blow Molding

Polymer Basics

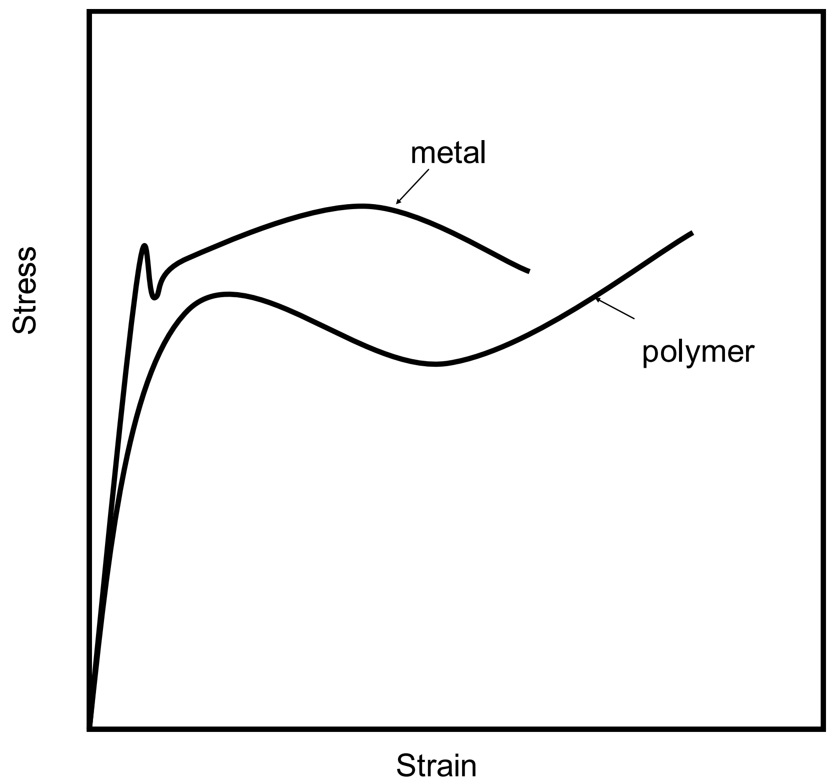
- Definition
  - poly = many
  - mer = basic recurring molecule
  - Polymers are long chain of recurring basic molecules



Polymer Properties

- Low density
- Low electrical and thermal conductivity
- Low strength and stiffness
- High strength-to-weight ratio
- Good resistance to chemicals
- Wide choice of colors and transparencies
- Ease of manufacturing
- Relatively low cost

Polymers: Mechanical Properties

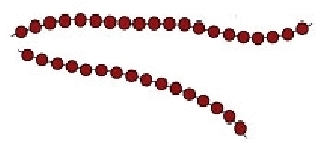


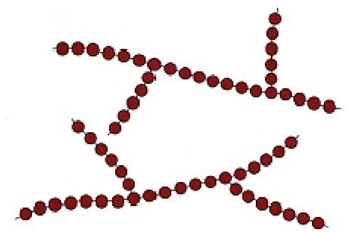
Comparison of metal and polymer

Polymer - Classification

- Thermoplastics
  - Molded and remolded by heating
  - posses linear and branched chains
  - PMMA, polycarbonate (PC), polyethylene (PE), PVC etc.

linear chain





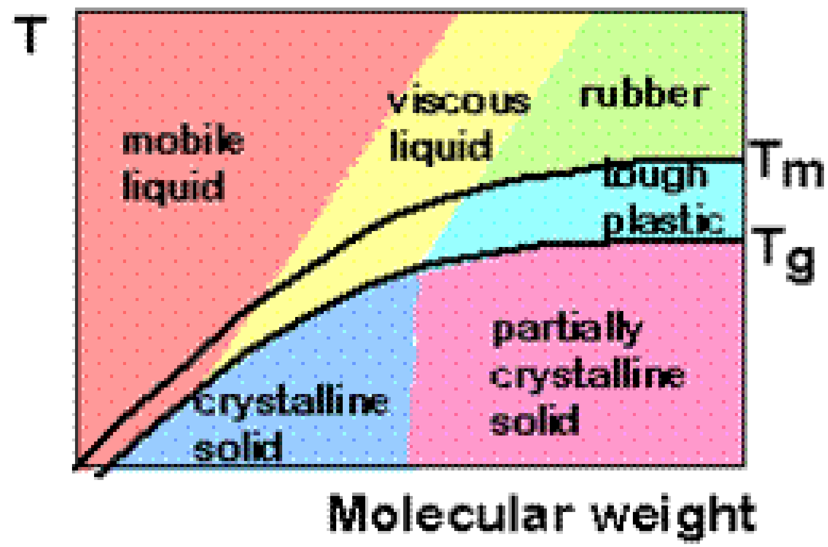
branched chain

- Thermosets
  - Solidify by being chemically cured during which long macromolecules cross-link with each other and cannot be remolded
  - Epoxy, polyester, polyimides etc.

Cross linked chain

Thermoplastics vs. Thermosets

- Thermoplastics
  - Little cross linking
  - Ductile
  - Soften with heat
- Thermosets
  - Large cross linking
  - Hard and brittle
  - Do not soften with heat



Polymer - Classification

- Elastomers
  - Undergo large extension without fracture and recover quickly after the load is removed (lightly cross-linked which permits almost full extension of molecules)
  - Rubber, Silicone etc.

Thermoplastics

Characteristics	Applications
• Mechanical properties vary with temperature • Exhibit creep behavior • Molecules oriented in direction of elongation • Hygroscopy (water absorption) in some thermoplastics • High coefficient of friction	• Bottles • Cable insulators • Tape • Blender bowls • Medical syringes • Textiles

Thermosets

Characteristics	Applications
• High thermal stability and insulating properties • High rigidity and dimensional stability • Resistance to creep and deformation under load • Light-weight	• Glues • Automobile body parts • Matrix for composites in boat hulls and tanks

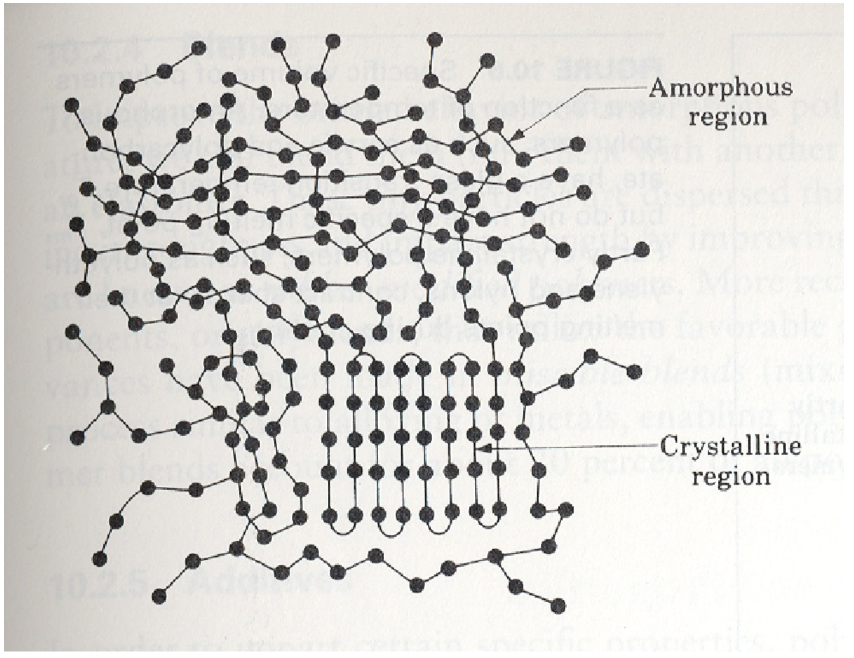
Elastomers

Characteristics	Applications
• Recover large deformation • High friction and nonskid surfaces • Corrosion resistance • Electrical insulation • Shock and vibration insulation	• Tires • Hoses • Footwear • Linings • Gaskets • Seals

Polymer - Classification

- Based on degree of crystallinity:

1. Amorphous
2. Semicrystalline



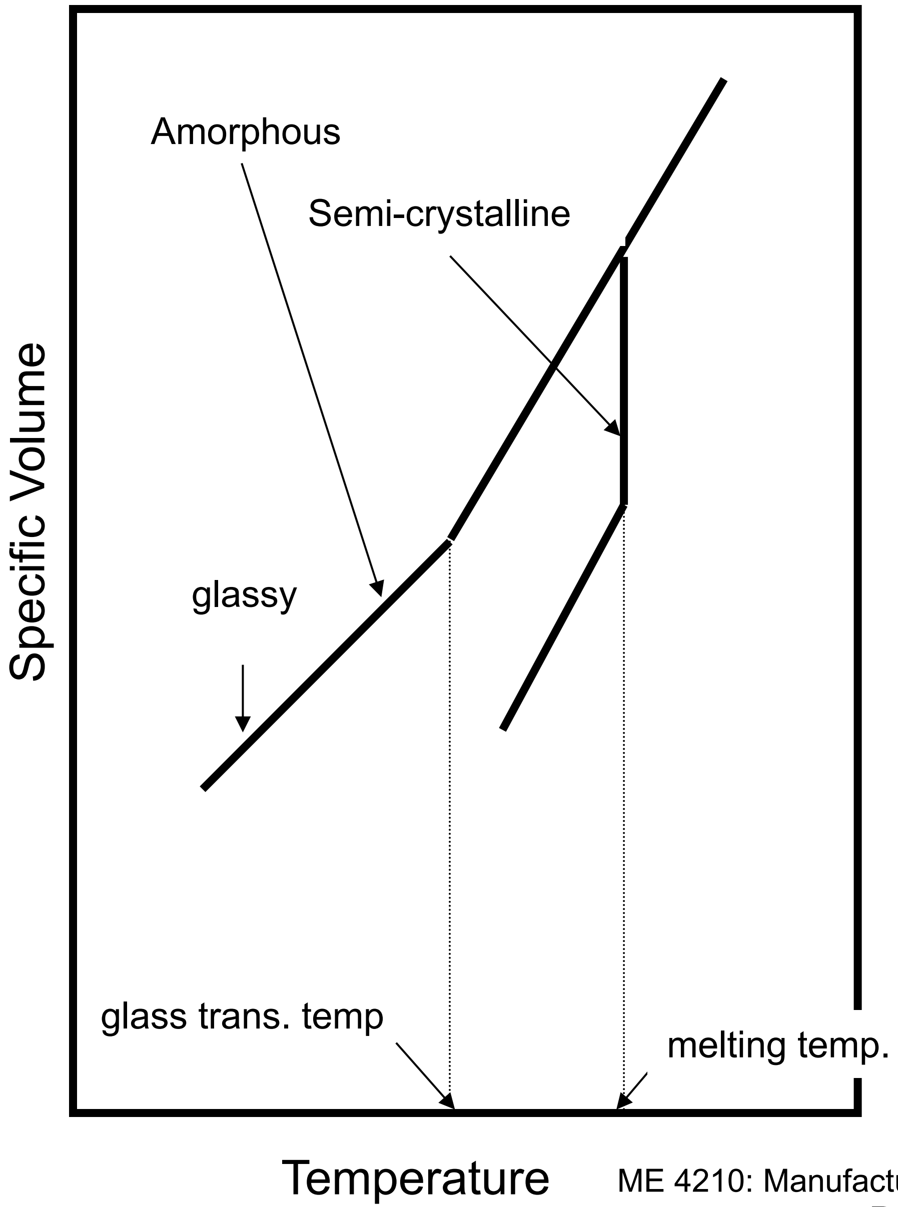
Polymer - Classification

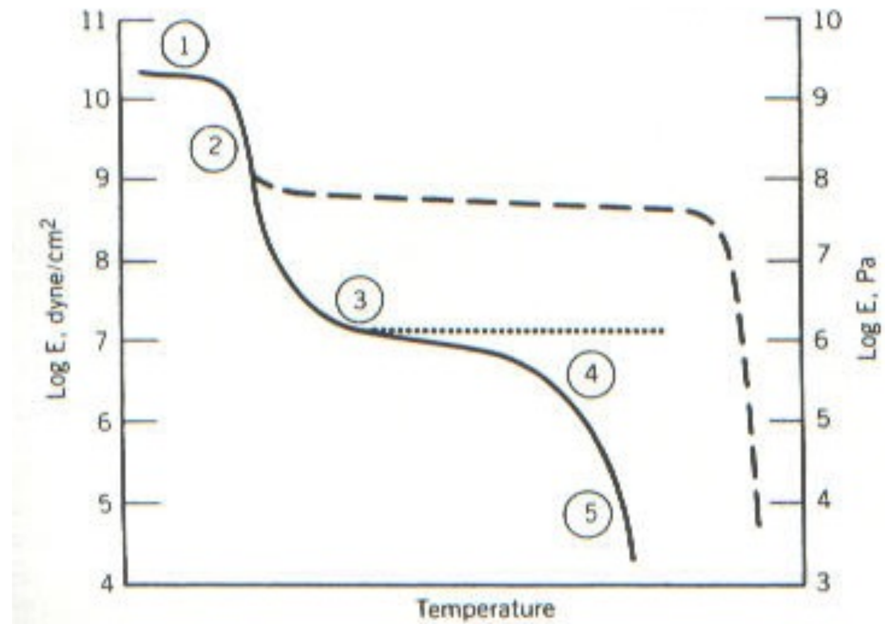
- Amorphous
  - Molecular chains intertwine with each other with irregular packing
  - Amorphous polymers exhibit a distinct change in mechanical properties across narrow range of temperatures

Polymer - Classification

- Semi-crystalline
  - Some molecular chains are packed in an orderly manner and some in an irregular manner
  - The degree of crystallinity greatly influences the mechanical and physical properties
  - With increase in degree of crystallinity, polymers become stiffer, harder, less ductile, denser and more resistant to heat

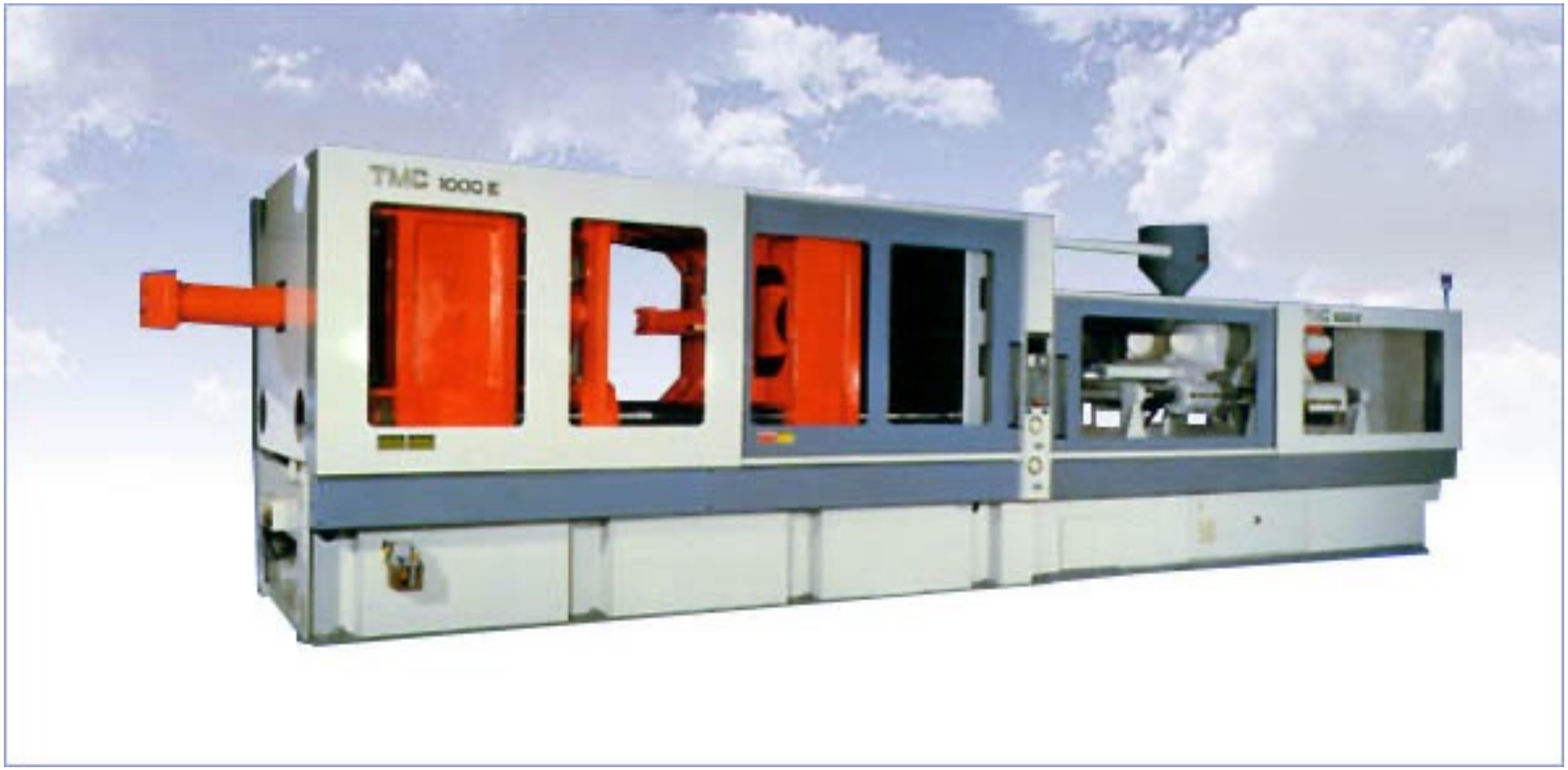
Properties – Amorphous Vs. Semi-crystalline



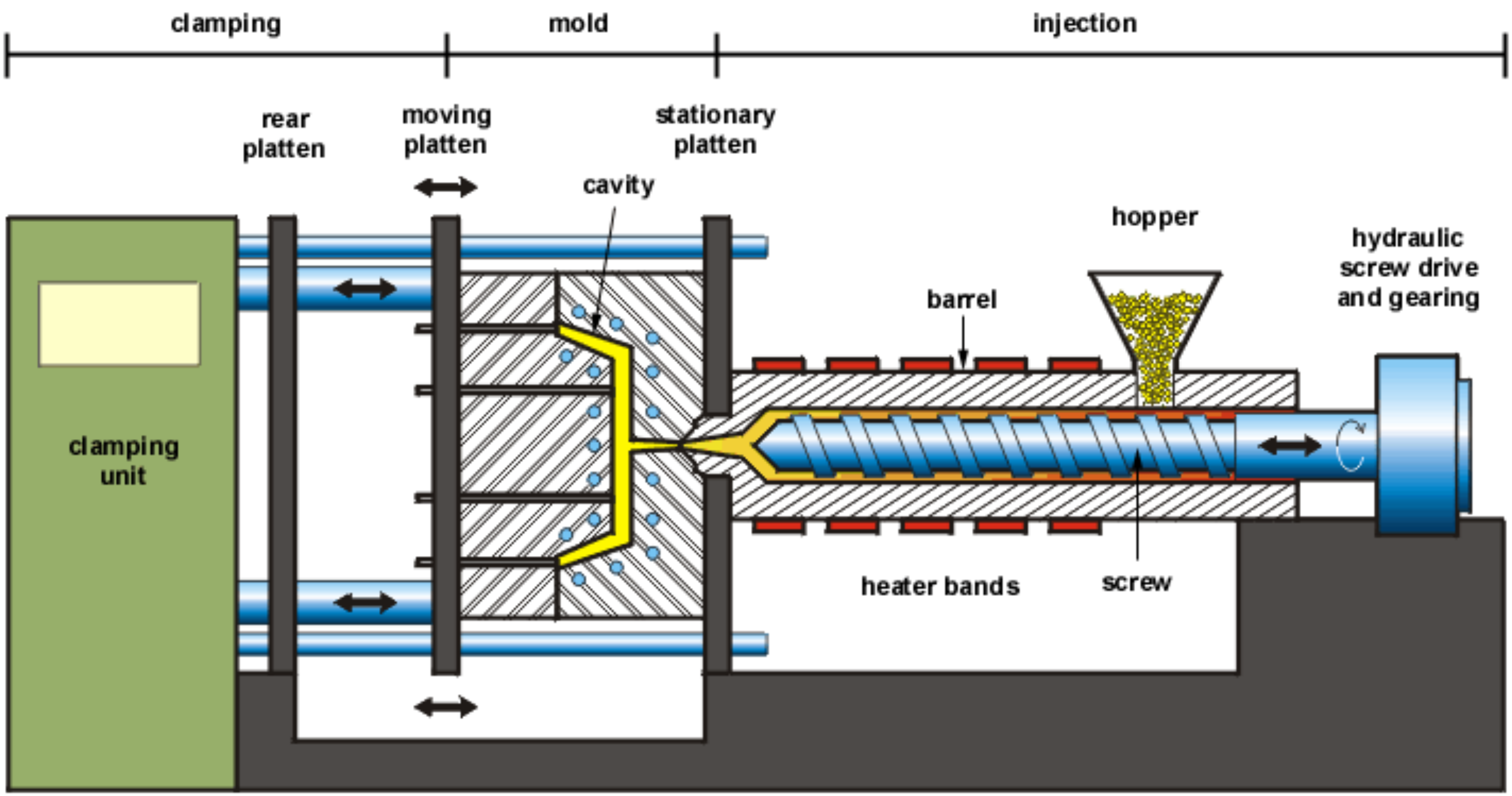


1. Glassy
2. Glass transition
3. Leathery
4. Rubbery
5. Viscous

Injection Molding Machine

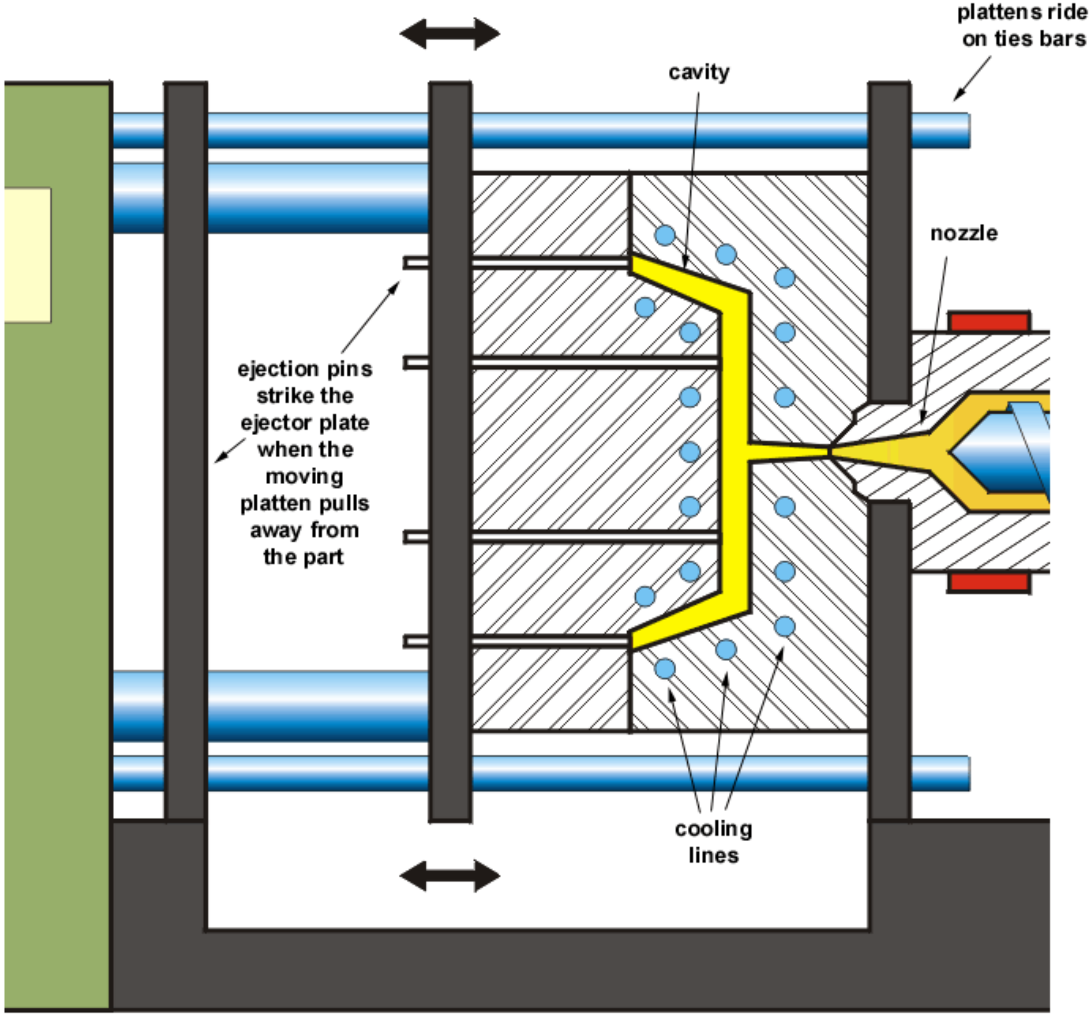


Injection Molding Schematic



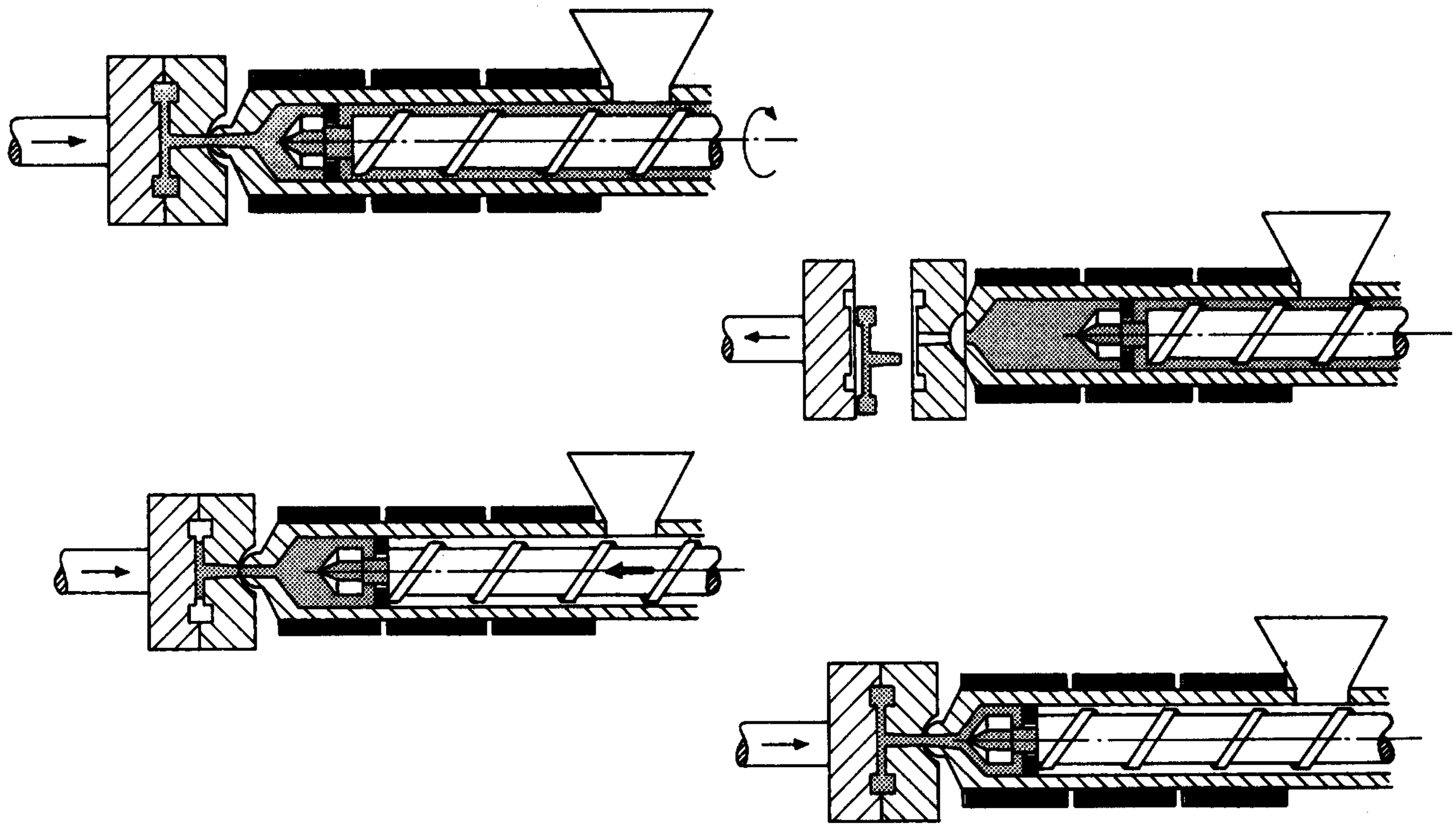
schematic of thermoplastic injection molding machine

Mold Schematic



mold area detail

Process

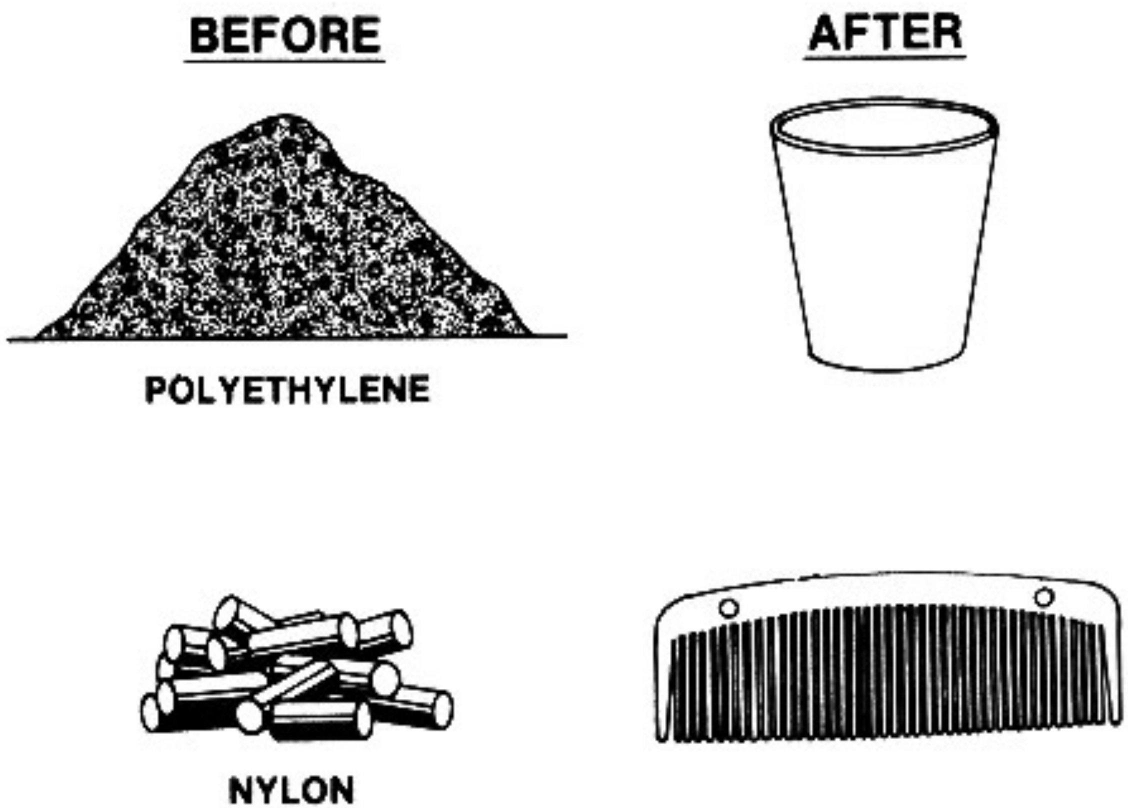


Process

- Pellets placed in hopper
- Pellets fall into barrel through throat
- Pellets packed to form solid bed
  - air forced out through hopper
- Pellets melted by mechanical shear between barrel and screw

Mold

Injection Molded Parts



Injection Molding

Process Characteristics

- Utilizes a ram or screw-type plunger to force molten plastic material into a mold cavity
- Produces a solid or open-ended shape conforming to the mold cavity
- Uses thermoplastic or thermoset materials
- Produces a parting line and sprue and gate marks
- Ejector pin marks are usually present

Process Capabilities

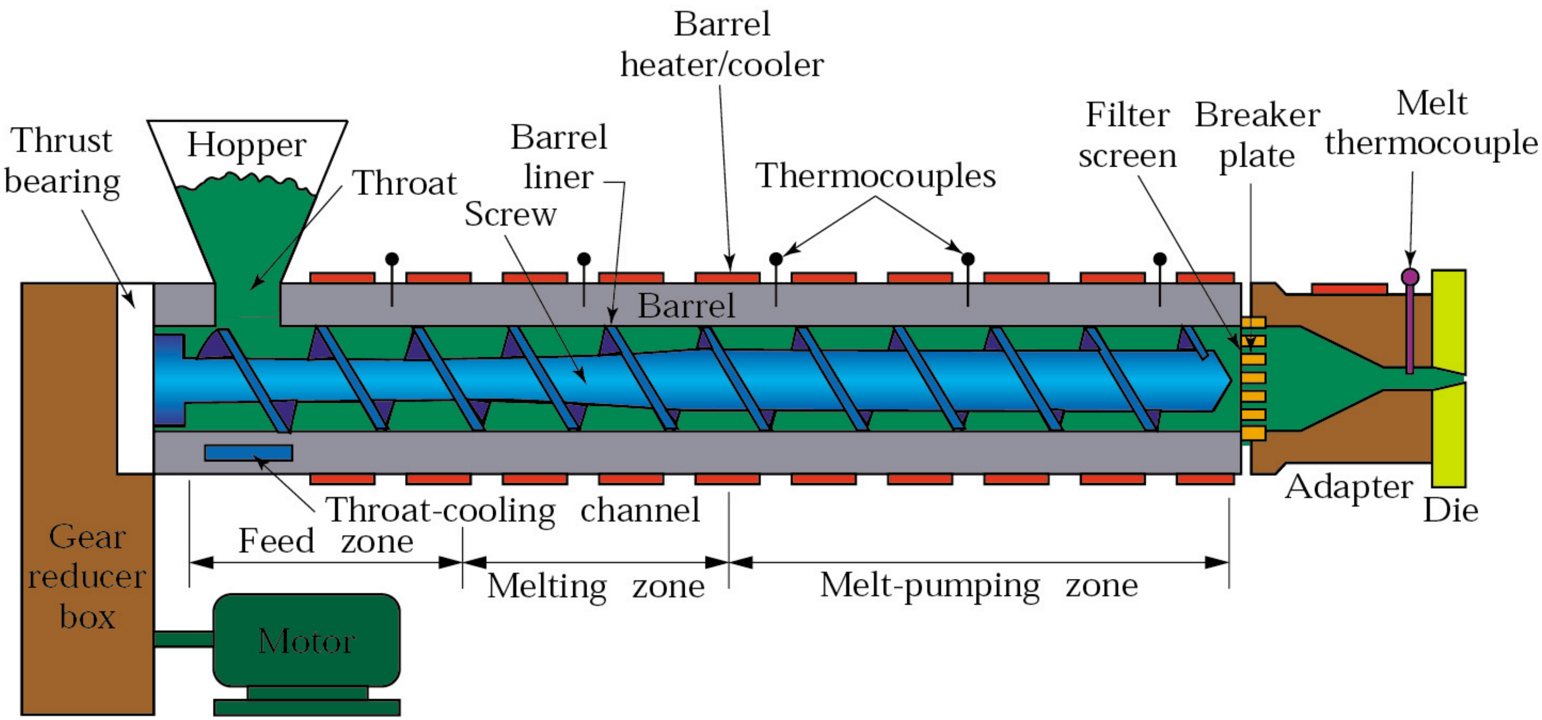
- Cycle time 10-60 s
- Economical for high production runs > 10,000
- Maximum section = 13 mm
- Minimum section = 0.4 mm for thermoplastics, 1 mm for thermosets
- Size = 10 g -25 kg for thermoplastics, 6 kg max. for thermosets
- Tolerance (typical)
  - $\pm$0.1 mm
- Surface roughness is a function of die condtion
  - 0.2-0.8 μm is obtainable

Injection Molding

- Advantages
  - Very complex shape and intricate details possible
  - Highly automatic process
  - Fast cycle time
  - Widest choice of materials

- Limitations
  - It has high capital cost
  - Economical for large numbers of parts
  - Large pressures in mold (20,000 psi)
  - Complicated runner and gating system

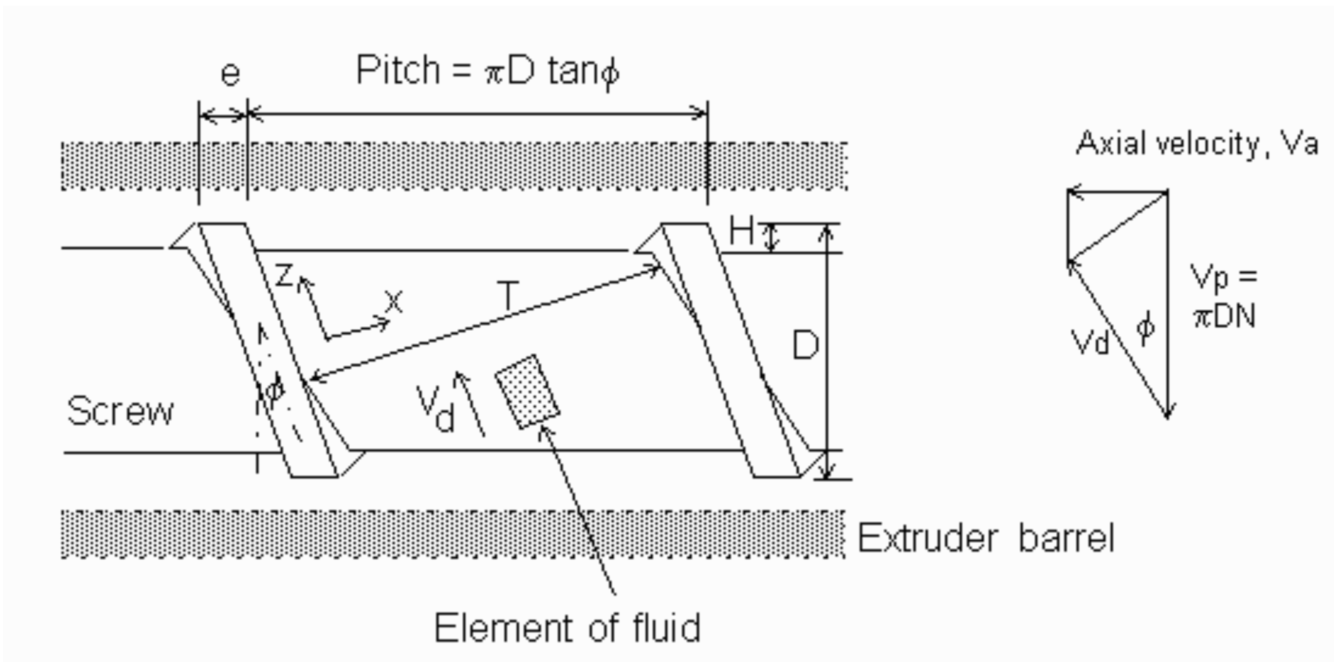
Extrusion



Barrel
heater/cooler
Thrust
bearing
Hopper
Throat
Barrel
liner
Screw
Thermocouples
Filter
screen
Breaker
plate
Melt
thermocouple
Barrel
Adapter
Die
Throat-cooling channel
Gear
reducer
box
Feed zone
Melting zone
Melt-pumping zone
Motor

Flow in screw - Injection molding and Extrusion

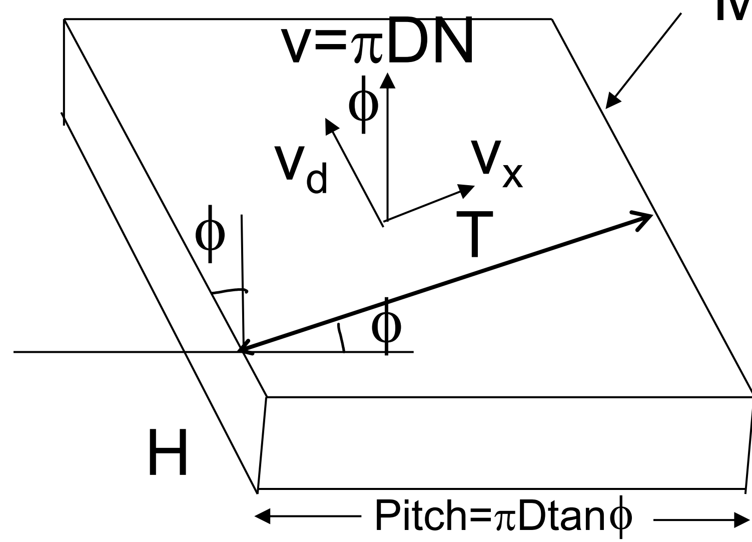
- Understood through simple fluid analysis
- Unroll barrel from screw
  - rectangular trough and lid



Flow analysis

- Barrel slides across channel at the helix angle
- v_d = drag
- v_x = stirring

Barrel is modeled as Moving top plate



Screw bottom is assumed as stationary

Flow rate

- v_d shows viscous traction work against exit pressure
- η

flow rate = f(exit pressure, v_d, η, T, h, L)

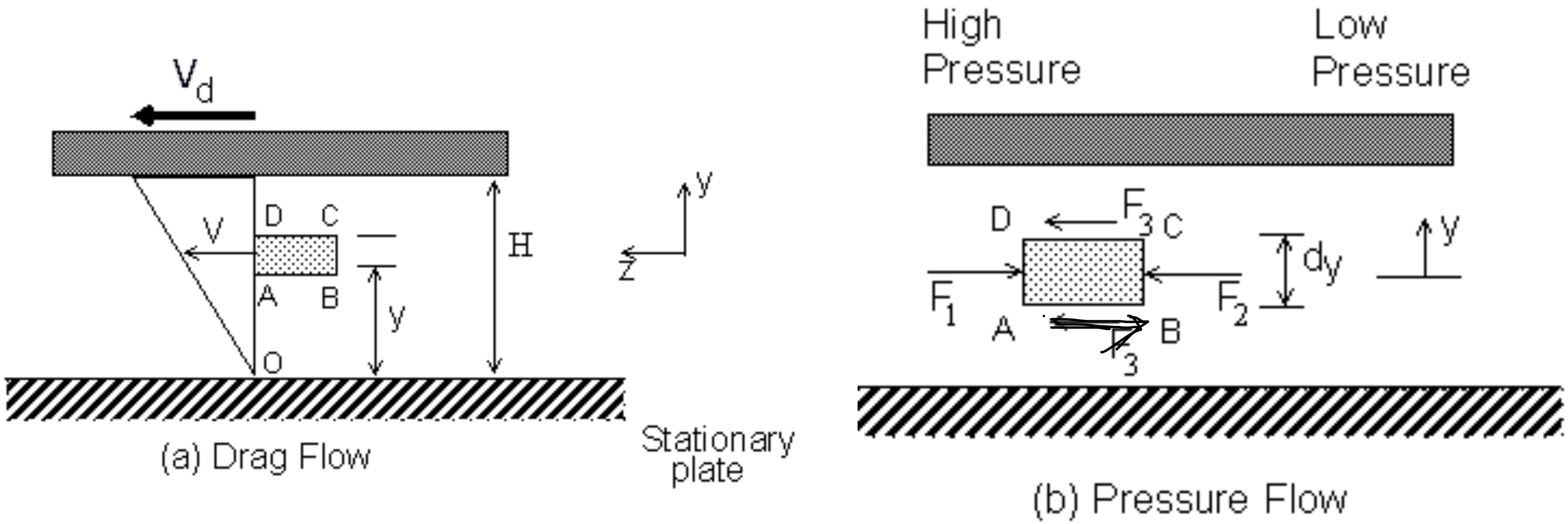
Analysis of Injection Molding

- Motivation
  – To compute flow rate of melt in the extruder

- Assumptions
  – Newtonian fluid
  – Separate into drag and pressure flows
  – No slip at walls
  – Incompressible
  – Laminar flow
  – End and side effects are negligible

Drag and Pressure Flow

- Drag Flow is due to the interaction of the rotating screw and stationary barrel.
- Pressure Flow due to the pressure gradient which is built up along the screw.



Drag and pressure flow

Drag Flow

- For the small element of fluid ABCD the volume flow rate dQ is given by:

$$dQ = V.\ dy\ .\ dx$$

- If the velocity gradient is assumed to be linear,

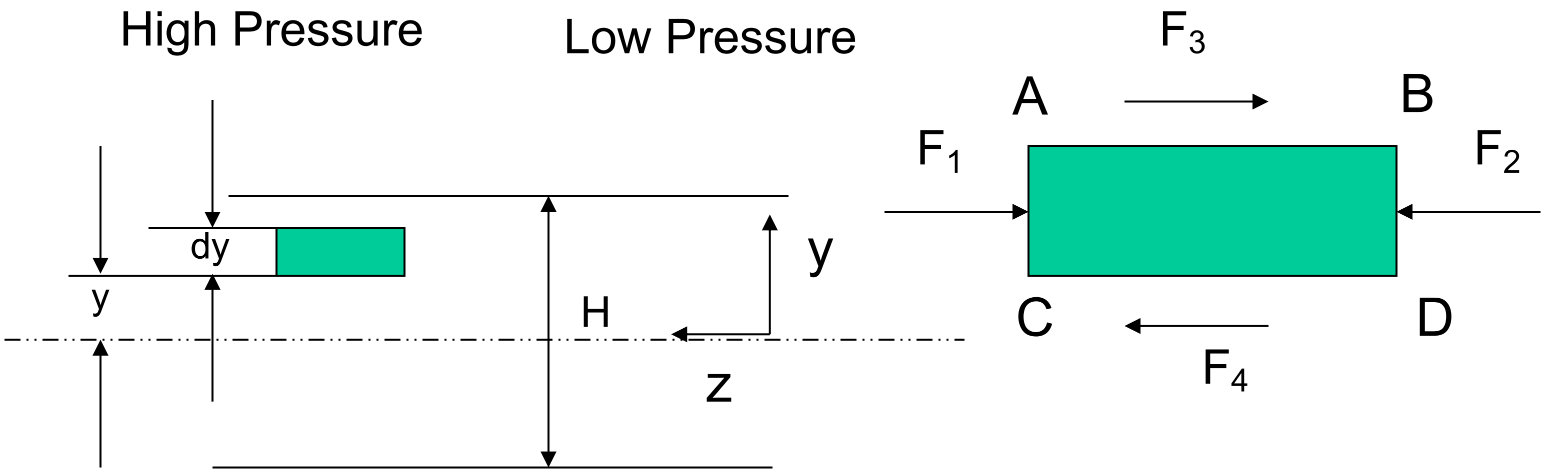
$$V = V_d\ (\ y / H\ )$$

$$Q_d = \int_0^H \int_0^T \frac{y.V_d}{H}.dy.dx$$

Hence,

$$\mathbf{Q_d = (1/2)\ T\ H\ V_d}$$

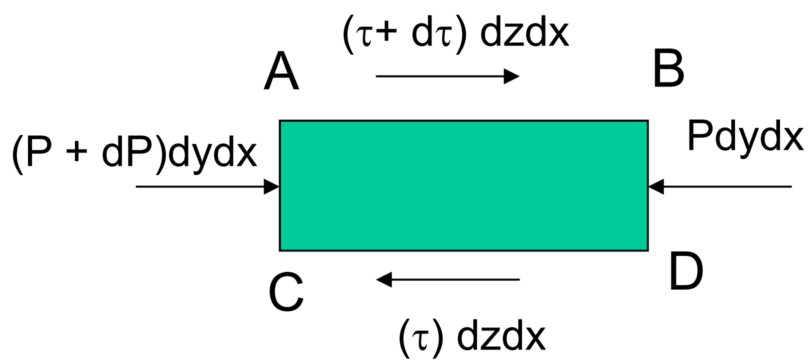
Pressure Flow



Free body diagram of the fluid element

Pressure Flow

- Let P be the pressure and τ be the shear stress acting on the fluid element ABCD. Hence, the forces acting on that element are:



Force balance yields,

$$\frac{dP}{dz}dy = -d\tau$$

Pressure Flow

Integrating the above equation to give the shear stress at any distance y from the centerline,

$$\int_0^{+y} \frac{dP}{dz}\,dy = -\int_0^{\tau_y} d\tau \longrightarrow -y\frac{dP}{dz} = \tau_y$$

$$\tau_y = \eta\,\dot{\gamma} = \eta\frac{dV}{dy}$$

Substituting and Integrating from base to a distance y from center,

$$-y\frac{dP}{dz} = \eta\frac{dV}{dy} \longrightarrow -\int_0^V dV = \frac{1}{\eta}\frac{dP}{dz}\int_{-H/2}^{y} y\,dy$$

$$-V = \frac{1}{\eta}\frac{dP}{dz}\left(\frac{y^2}{2} - \frac{H^2}{8}\right)$$

Pressure Flow

Now, the volume flow rate is given by:

$$dQ = V\ T\ dy$$

Substituting for V and integrating to get the pressure flow, Q_p

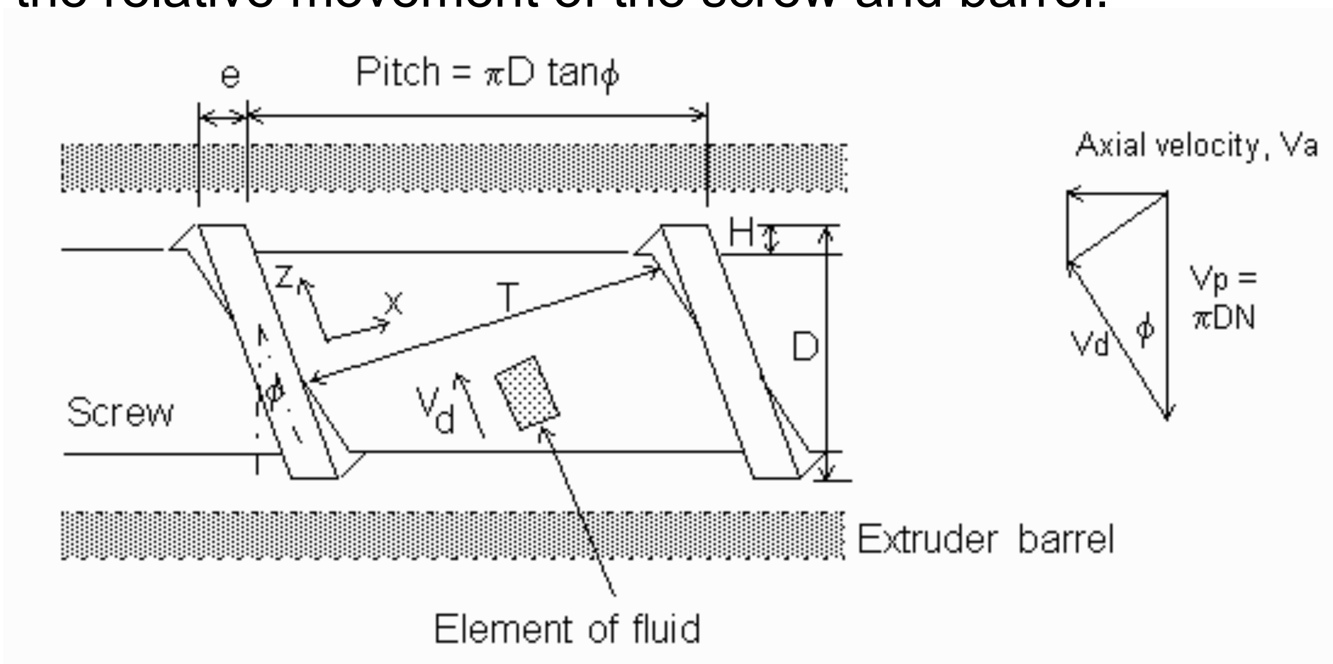
$$Q_p = -\frac{1}{12\eta}\frac{dP}{dz}.TH^3$$

$$Q = Q_d + Q_p$$

$$Q = (1/2)\ T\ H\ V_d\ -\frac{1}{12\eta}\frac{dP}{dz}.TH^3$$

Pressure Flow

We are interested in the fluid flow in the extruder as it is dragged along by the relative movement of the screw and barrel.



Details of extruder screw

Pressure Flow

For the case shown in extruder, where the fluid element is between the two flights, assuming e is small, T is approximated by:

$$V_d = V_{barrel}.\cos\varphi$$
$$V_d = \pi DN.\cos\varphi$$

$$T = \pi D \tan\varphi\cos\varphi$$

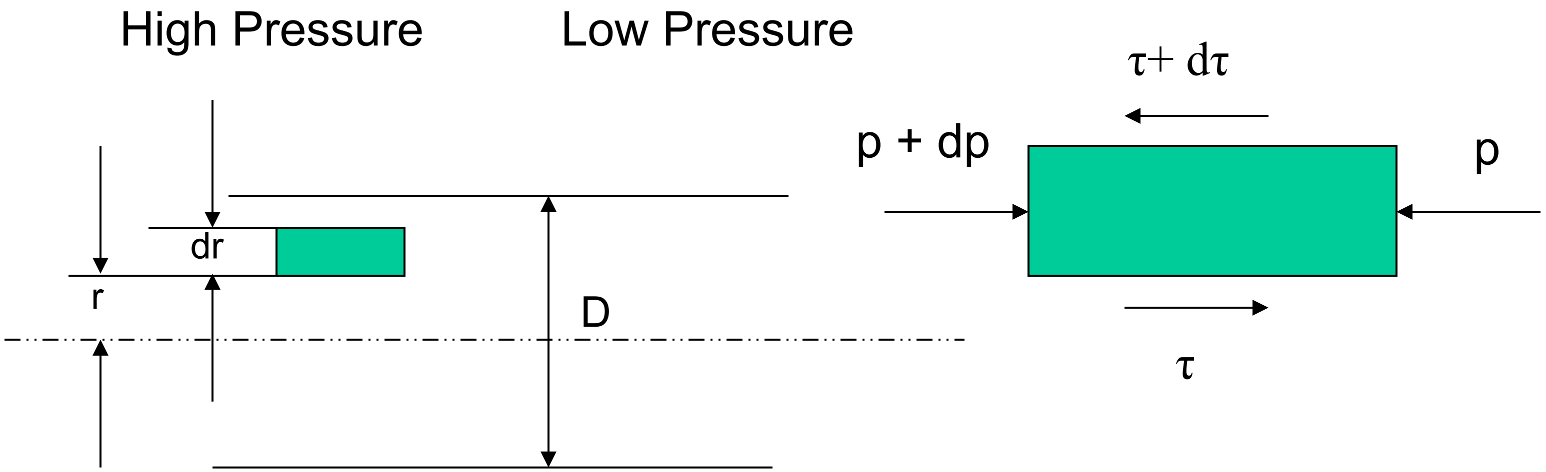
where,

$$\sin\varphi = \frac{dL}{dz} \quad \text{and} \quad \frac{dP}{dz} = \frac{dP}{dL}\sin\varphi$$

In terms of extruder geometry,

$$Q_p = -\frac{\pi D H^3 \sin^2\varphi}{12\eta}\frac{dP}{dL}$$

Flow in Round Runner or Die



Free body diagram of the fluid element

Flow in Round Runner or Die

Equilibrium equation will yield,

$$\pi \cdot [(r+dr)^2 - r^2] \cdot dp = 2\pi \cdot [(r+dr)\cdot(\tau + d\tau) - r\tau] \cdot dz$$

Integrating and applying boundary conditions total flow is,

$$Q_p = \int_0^R 2\pi r \cdot u \cdot dr = \frac{\pi \cdot R^4}{8\eta} \cdot \frac{\Delta p}{L}$$

Example

You are extruding a polymer material through a steel die. The density of the polymer is 980 kg/m^3. At processing temperature, its viscosity (μ) is 10^3 $N\text{-}s/m^2$. The internal diameter (D) of the barrel of the machine's extruder is 28 mm, with a flight width (T) of 21 mm, and a flight depth (H) of 4 mm. The helix angle of the screw (φ) is 15 degrees. The screw is 1.25 m in axial length. The die is a cylinder 5 mm in diameter and 40 mm long. You may assume the barrel rotates and the screw is stationary. Determine the RPM of the screw to make product at a linear velocity of 10 cm/s?

Solution

The melt enters the die from the extruder hence for steady state the flow rate should be the same and the pressure drop should also be the same:

$Q_{extruder} = Q_{die}$

$\Delta P_{extruder} = \Delta P_{die}$

Given:

V_{die} = 10 cm/s	H = 4 mm	$L_{extruder}$ = 1.25 m
D_{die} = 5 mm	D_{barrel} = 28 mm	L_{die} = 40 mm

$$Q_{die} = A_{die} . v_{die}$$
$$= \pi/4 . (5 \times 10^{-3})^2 . (0.1)$$
$$= 1.963 \times 10^{-6}$$

Solution

From round die analysis,

$$Q_{die} = \frac{\pi \cdot R^4}{8\,\eta} \cdot \frac{\Delta p}{L}$$

$$\frac{\pi(2.5\times10^{-3})^4\,\Delta P}{8(10^3)(40\times10^{-3})} = 1.96\times10^{-6}$$

ΔP = 5.12 MPa

Using the extruder flow,

$$Q_{extruder} = (1/2)\ T\ H\ V_d - \frac{1}{12\eta}\frac{dP}{dz}.TH^3$$

Solution

$$\frac{dP}{dz} = \frac{\Delta P}{L_{extruder} \big/ \sin\varphi}$$

Solving for V_d (velocity in the barrel channel),

V_d = 0.0467 m/s

$V_d = V_{barrel}.\cos\varphi$

$V_{barrel} = \dfrac{\pi DN}{60}$

N = 33.01 rpm

Injection molding cycle

1. To make a shot: use screw (extruder) equation for flow rate (Q) to produce a shot volume (vol = Q*t).
   - back pressure gives dp term
   - time (t) bounded by cycle time (upper) and degradation of material (lower)

Injection molding cycle

2. To inject the plastic: use pressure flow equations and injection pressure (Δp) or injection time (t) and volume to be filled (shot volume) to determine flow rate (Q) and hence time (t) or injection pressure (Δp) required to fill mold
   - injection time (t) will be limited by freezing of plastic and degradation of material

Injection Molding - Ex. 1-1

- Injection mold a polymer in a steel tool
- Model the sprue, runner and part as a cylinder of diameter 10 mm, length 150 mm
- Determine the screw RPM to make a shot in less than 3 seconds (Assume screw rotates)
- Determine the injection pressure to make the part in 2 seconds

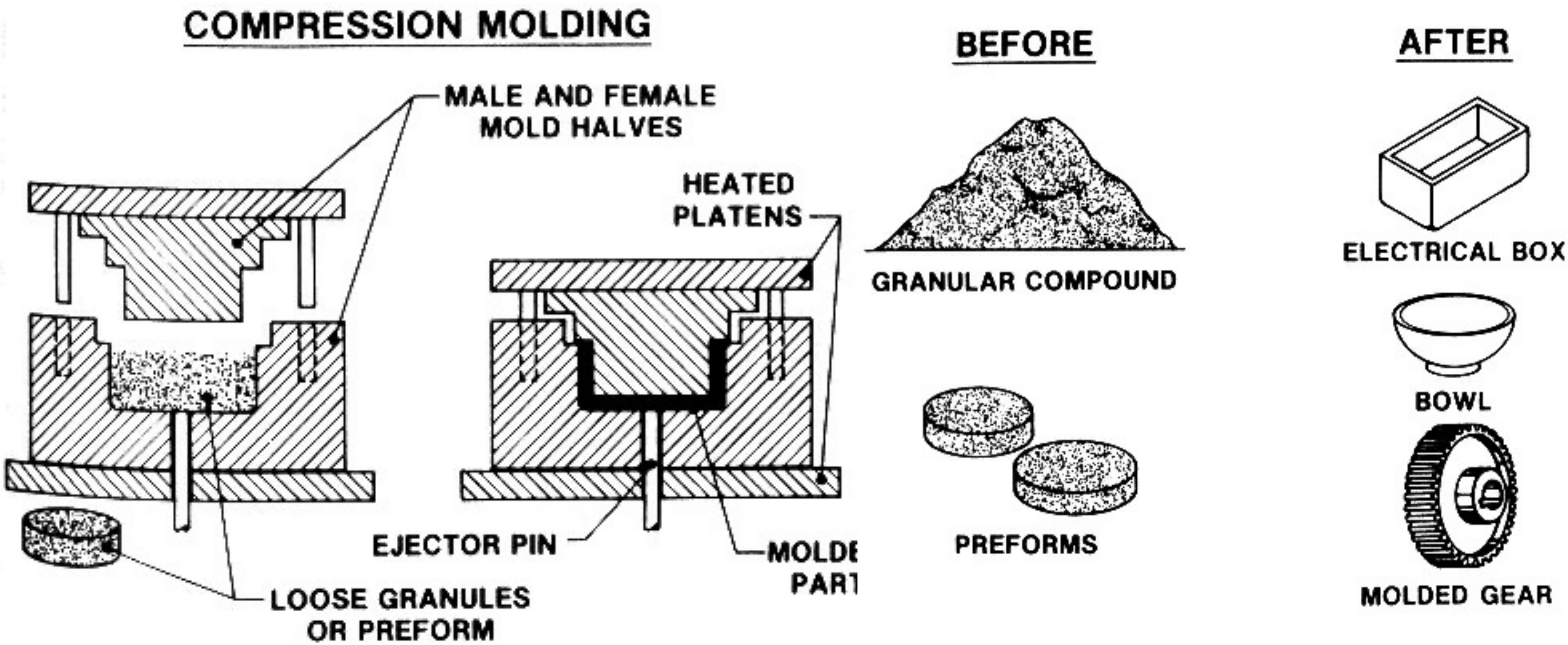
Injection Molding - Ex. 1-2

- polymer density (ρ) = 980 kg/m^3
- polymer viscosity (η) = 10^3 N-s/m^2
- barrel diameter (D) = 28 mm
- flight width (w) = 21 mm
- flight height (H) = 4 mm
- helix angle (ϕ) = 15 degrees
- length of screw (L) = 1.25 m

Injection Molding - Ex. 1-3

- Screw RPM calculation
- Back pressure = 15 MPa
- Assume 3 seconds to make shot
- Calculate Q

Compression Molding



Process Characteristics

- Uses thermoset preforms or granules
- Materials are usually preheated
- Material must be accurately measured to maintain uniform size or to avoid excess flash
- Metallic inserts may be molded into the product
- Shape must not have undercuts
- Requires no sprues, gates, or runners

Process Capabilities

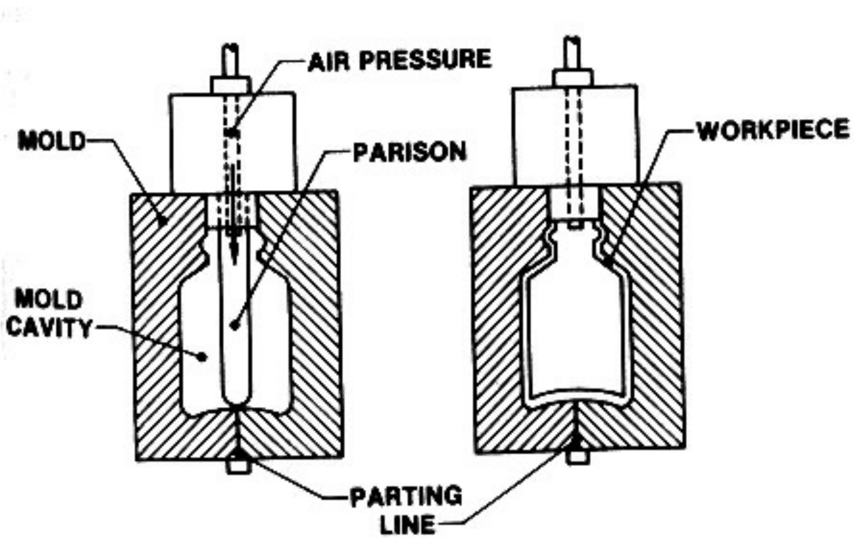
- Cycle time 20-600 s
- Production runs > 1,000 may be 100 for small parts
- Maximum section = 25 mm
- Minimum section = 0.25 mm
- Size = 10 g -15 kg
- Allowance
  - $\pm$0.1 mm
- Surface roughness is a function of die condition
  - 0.2-0.8 μm is obtainable

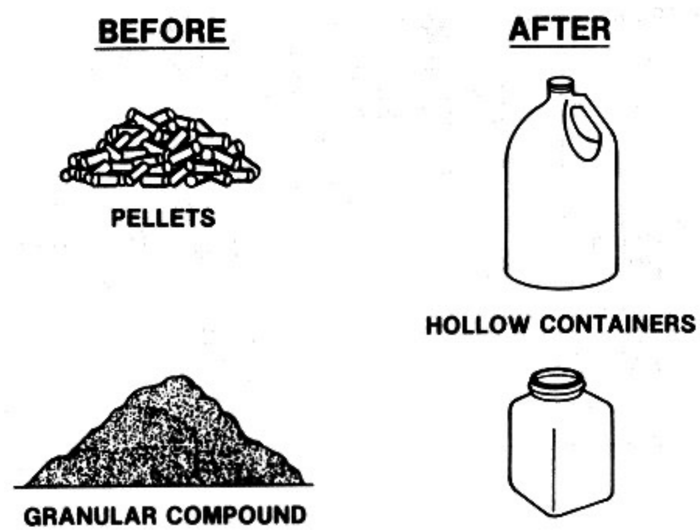
Compression Molding

- Advantages
  - It has lower mold pressures (1000 psi)
  - Minimum damage to reinforcing fibers (in composites)
  - Large parts are possible

- Limitations
  - Very complex shape and intricate details not possible
  - Requires more labor
  - longer cycle than injection molding
  - Each charge is loaded by hand
  - Air entrapment possible

Blow Molding





Process Characteristics

- Inflates a softened parison tube to the contour of a mold cavity
- Uses thermoplastics
- Forms thin-walled hollow products
- Parting lines are present
- Wall thickness can be increased by increasing the parison tube wall thickness
- Flash is present but is minimal

Process Capabilities

- Production rates 100-2500 pieces/hr
- Production runs can be as high as 10,000,000
- Maximum section = 6 mm
- Minimum section = 0.25 mm
- Size = 10 g -15 kg
- Tolerance (typical)
  - $\pm$0.1 mm
- Surface roughness is a function of pressure

Blow Molding

- Advantages
  - It can make hollow parts (especially bottles)
  - Stretching action improves mechanical properties
  - Has a fast cycle
  - Not labor intensive

- Limitations
  - It has no direct control over wall thickness
  - Cannot mold small details with high precision
  - Requires a polymer with high melt strength

Summary

- Polymer properties
- Injection molding basics
- Analysis of polymer flow
- Compression molding
- Blow molding